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**AFWAL-TM-84-210-FIEM**

**AN EXPERIMENTAL INVESTIGATION OF  
AIR CUSHION FLUTTER USING A TWO-  
DIMENSIONAL TRUNK MODEL**

**PETER C. VORUM**

**APRIL 1984**

**FINAL REPORT FOR PERIOD 12/07/80 - 04/01/83**



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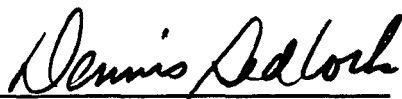
THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.



PETER C. VORUM  
Project Engineer  
AFRL/MLBT



DAVID J. PEREZ, Chief  
Plans and Programs Branch  
Integration and Operations Division



DENNIS SEDLOCK  
Chief, Flight Systems Division  
Air Vehicles Division

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## LIST OF ABBREVIATIONS

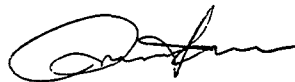
SYMBOL	DESCRIPTION	UNITS
2D	Two Dimensional	
3D	Three Dimensional	
ACLS	Air Cushion Landing System	
D	Diameter	feet
f	Frequency	Hertz
V	Velocity	feet/second
P <sub>c</sub>	Cushion Pressure	pounds per square inch gage or pounds per square foot gage
β	Diameter of orifice/diameter upstream	
Q	Volume flow rate	cubic feet per minute
P <sub>i</sub>	Static pressure upstream of the orifice	psig
IGE	In Ground Effect	i.e. state of positive cushion pressure
OGE	Out of Ground Effect	state of zero cushion pressure
dBa	Sound Pressure Level, "a" weighted scale	Decibels

## FOREWORD

This Technical Memorandum describes an in-house effort conducted by personnel of the Special Projects Group, Mechanical Branch, Vehicle Equipment Division, of the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, at Wright-Patterson Air Force Base, Ohio, under Project Number 2402, Task Number 24021, Work Unit Number 24020129. It covers tests conducted between December 1980 and April 1983 under the direction of the author, Peter C. Vorum, Project Engineer. The Technical Memorandum was released by the author in April 1984.

The author wishes to express appreciation to David J. Pool and Gwen A. Patterson of the Special Projects Group for their assistance in performing the tests, to Professor Harold C. Larsen, Air Force Institute of Technology, for his technical guidance, and Deborah D. Long for clerical support in the preparation of this report.

This Technical Memorandum has been reviewed and is approved.



AIVARS V. PETERSONS, Chief  
Mechanical Branch  
Vehicle Equipment Division  
Flight Dynamics Laboratory

## SECTION I SUMMARY

This program was an in-house project, to test the effectiveness of flutter control elements on an air cushion trunk. A single inelastic trunk carcass was used throughout the program. Individual elements were added to change the stiffness or mass of the fabric, or to control the air flow under the trunk. The elements were tested individually and together. None of the elements was permanently attached to the trunk: rubber cement and duct tape were used to secure them. The motions of the trunk were observed under a variety of pressure and ground clearance settings. Manual data collections were made. Although the fabric used here was lighter than that used on the full-scale XC-8A aircraft tests, the performance of this quarter-scale rig was similar to what was seen on the actual aircraft. These passive elements did affect the amount of control force required to stop the large amplitude heave oscillations. Based on these tests, recommendations were made to produce a light, effective trunk system free of flutter.

## SECTION II INTRODUCTION

### 1.0 Objective

The objective of this test program was to measure performance changes when passive control elements were added to a two dimensional (2D) quarter scale model of the XC-8A Air Cushion Landing System (ACLS). See References 1; Figures 1, 2, and 3. Operating points were established at a number of trunk pressures, and vertical clearances between the ground plane and the hard structure. These tests were performed in-house in the Vibration and Aeroelastic Facility of the Flight Dynamics Laboratory at Wright-Patterson AFB, Ohio. Unlike other programs, these tests were run on a continuous flow system that permitted time to record numerical data and to make visual observations. A single trunk was tested alone and with the control elements added.

### 2.0 Background

Trunk flutter has been noted in a number of different air cushion systems. The loss of load bearing capacity, a reduction of handling ease, and damage to the trunk fabric have all been recorded. The high noise levels generated (116 dBa was recorded during one in-house test) may contribute to structural fatigue and do necessitate hearing protection for operating area personnel.

These tests examined the effect of adding fabric panels, discrete weights, a strake perpendicular to the flow, and tread strips parallel to the flow, to the simple trunk carcass; using bleed systems to vary trunk and cushion flow rates independently; and forcing the flow to remain attached to the trunk panel downstream of the ground contact region. Other tests have also studied the effect of changing the trunk hole pattern near the ground plane. This last procedure was not pursued on the single, uniform, light weight, inelastic carcass used for these tests. See References 2-6.

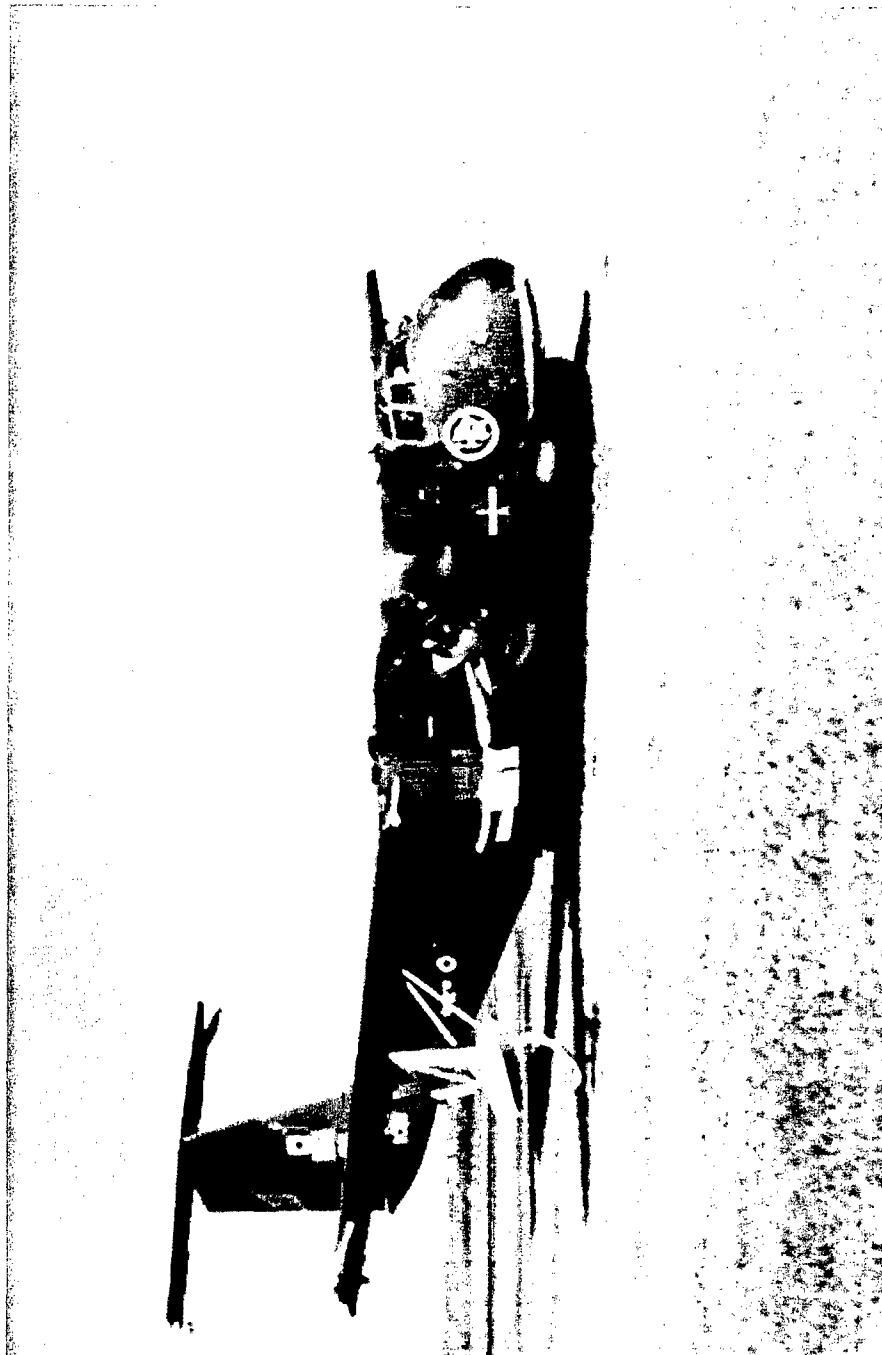


FIGURE 1. XC-8A AIRCRAFT with TRUNK INFLATED

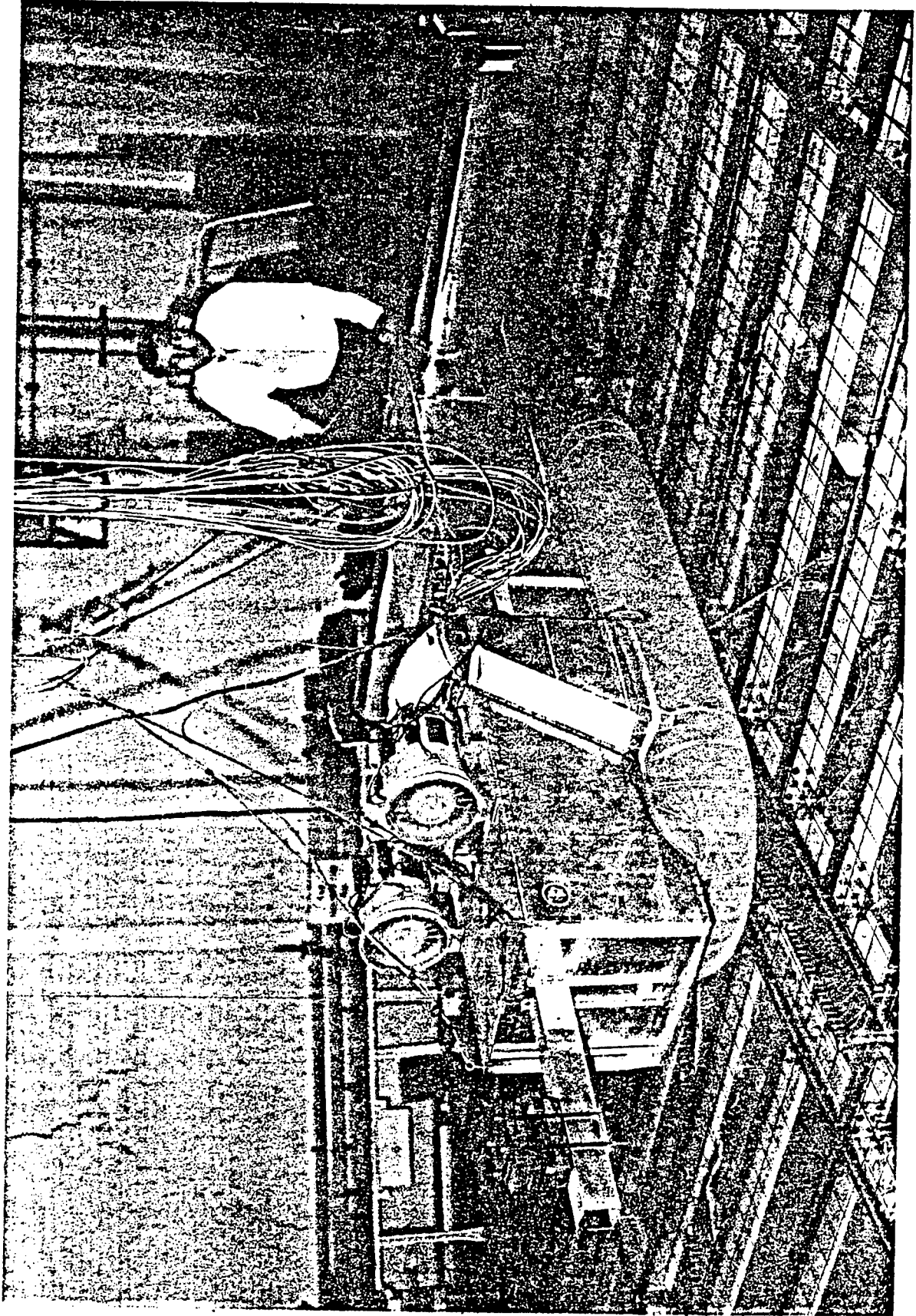


FIGURE 2. QUARTER SCALE XC-8A 3-D TEST MODEL

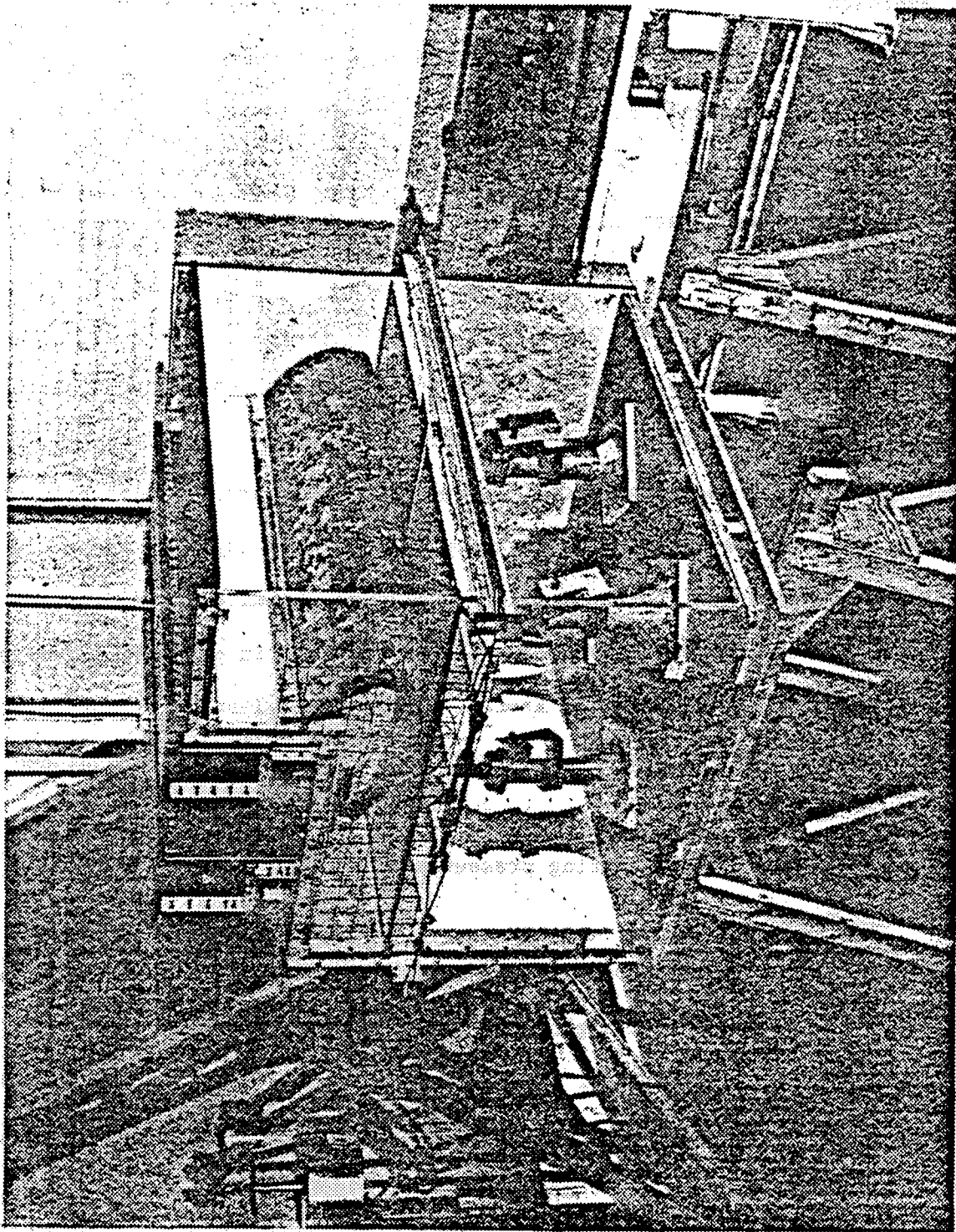


FIGURE 3. 2-D FLUTTER RIG

### 3.0 Approach

A 2D rig (see Figure 3) was constructed in the envelope of a four (4) foot cube, built to permit nine (9) inches of vertical adjustment of the trunk outer attachment location, and twenty four (24) inches of horizontal adjustment of the trunk inner attachment location. The movable floor panel could be adjusted to give zero (0) to twenty eight (28) inches of clearance between the hard structure and the ground plane (see Figure 4).

The trunk carcass was made of Snyder NRV-1814, a nylon reinforced vinyl fabric that weights eighteen (18) ounces per square yard (see References 7 and 8, and Appendix A). Because of low operating pressures (0.6865 psig trunk pressure maximum), and the materials characteristics of 1814, an elongation of 4% or less was observed (see Appendix B). With this limited loading, the fabric was considered "inelastic": i.e., no change in physical dimensions between the inflated and deflated states. The torsional stiffness of 1814 was not measured, but it was observed to be low: when a pencil was placed parallel to the air flow under the trunk, the fabric conformed easily around it when the trunk was at operating pressures.

### 4.0 Fabric Motion

The general fabric motion was very dramatic. The trunk moved in rhythmic heave-like motion slapping the ground. A maximum air gap at the center of the bag as great as one and one-half (1-1/2) inches was seen (see Figure 5). One combination of trunk and cushion manifold air flows set up such large motions that the entire 450 pound rig began to walk across the cell floor. The movable floor and the bottom panel of the rig had to be reinforced to reduce the flexing of those panels caused by the bag motion.

Node points were identified at two (2) inch intervals along a line parallel to the air flow. Thread was sewn in lines through the node points perpendicular to the air flow, the

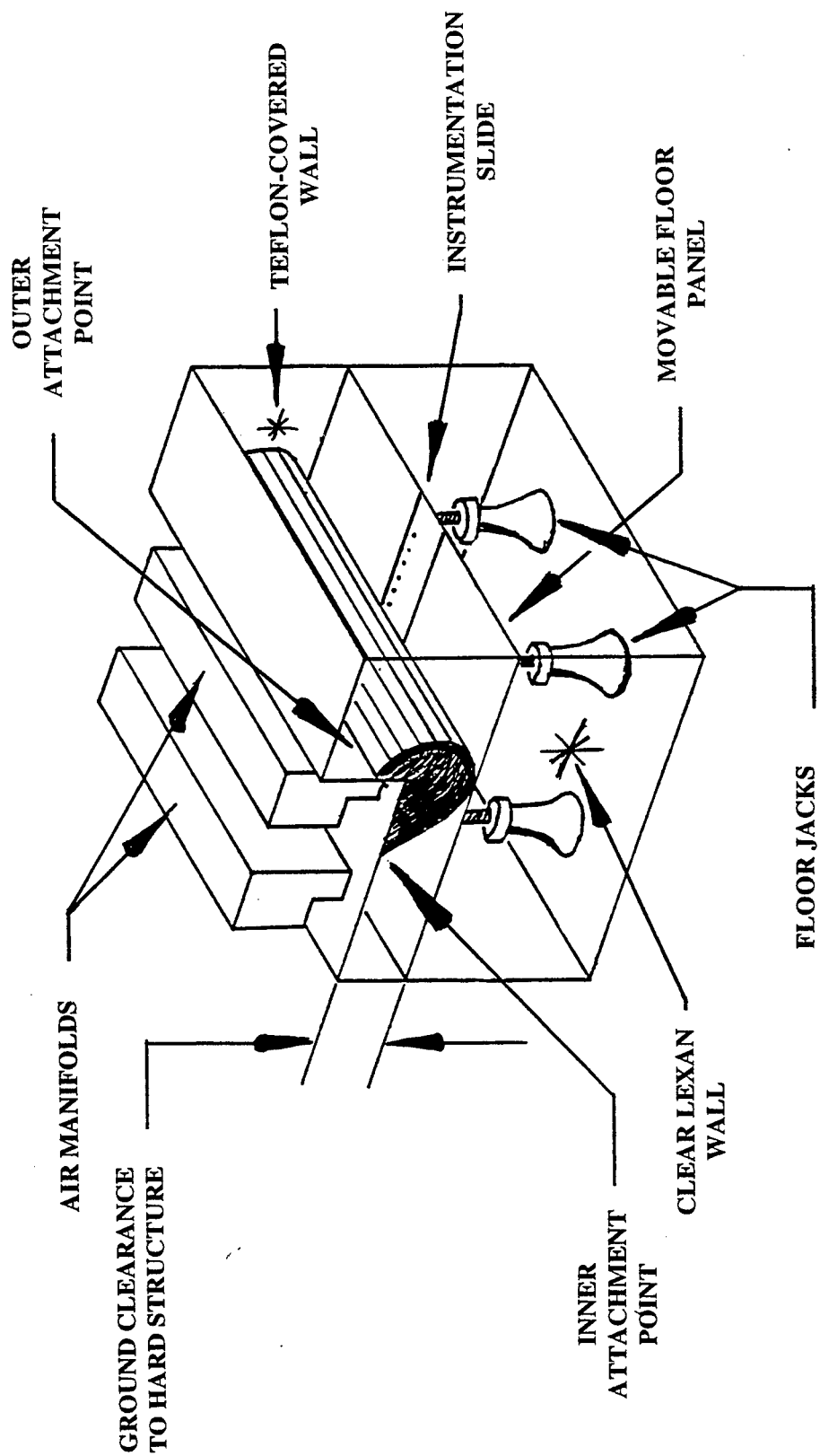
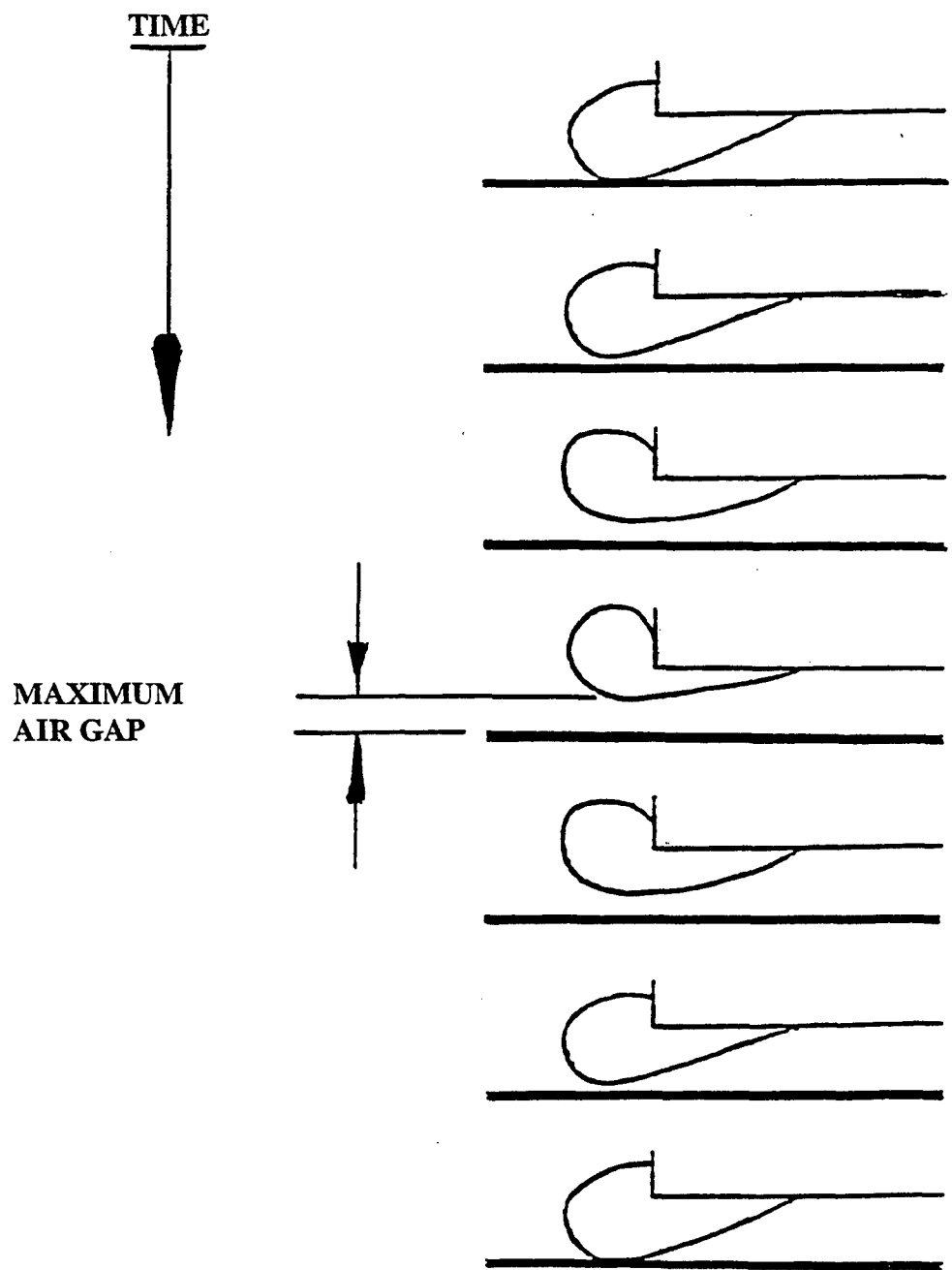


FIGURE 4. 2-D FLUTTER RIG ELEMENTS



**FIGURE 5. TRUNK HEAVE during FLUTTER**

full width of the bag. These lines helped observers follow the trunk motion with a strobe light. In all tests, ground contact varied from a tangent line at node 6, to a three (3) inch by forty eight (48) inch strip located between nodes 6 and 7-1/2, regardless of the ground clearance to the hard structure (see Figure 6).

In addition to the large amplitude heave motion, small waves were also present in the fabric. These waves moved from node 6 as the bag rose, reflected off the inner and outer attachments as the bag was at its highest point, and traveled back to node 6 as the bag dropped to the floor again. The wave that traveled to the inner joint was only visible in the side wall sealing cuff. The wave in the outer portion was visible along the entire length of the trunk fabric. See Reference 9, Figure 7. Only when sawtooth panels were added to the trunk, changing the system weight and stiffness, did the pattern vary. Then the two waves met near node 8 as the bag was rising.

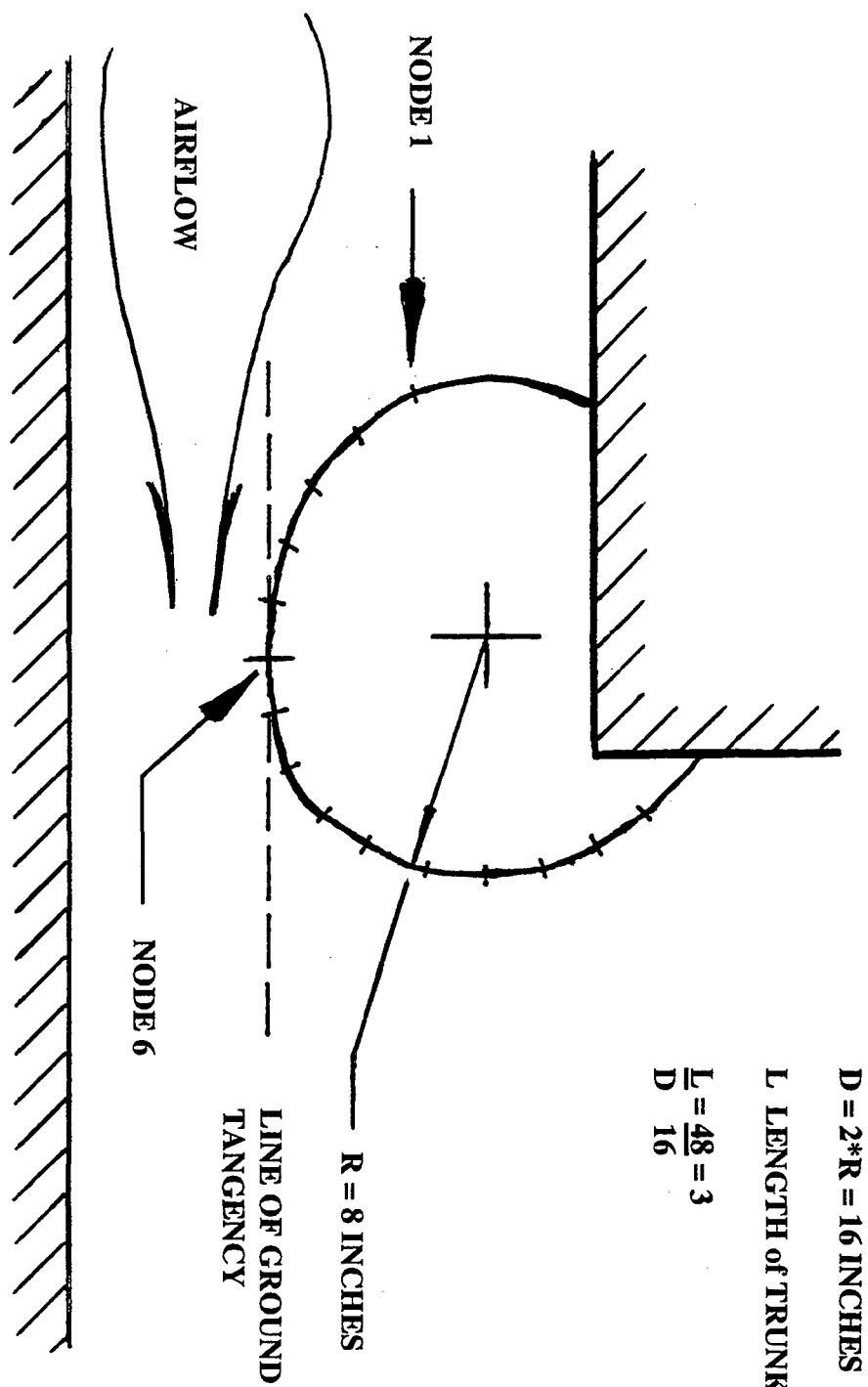
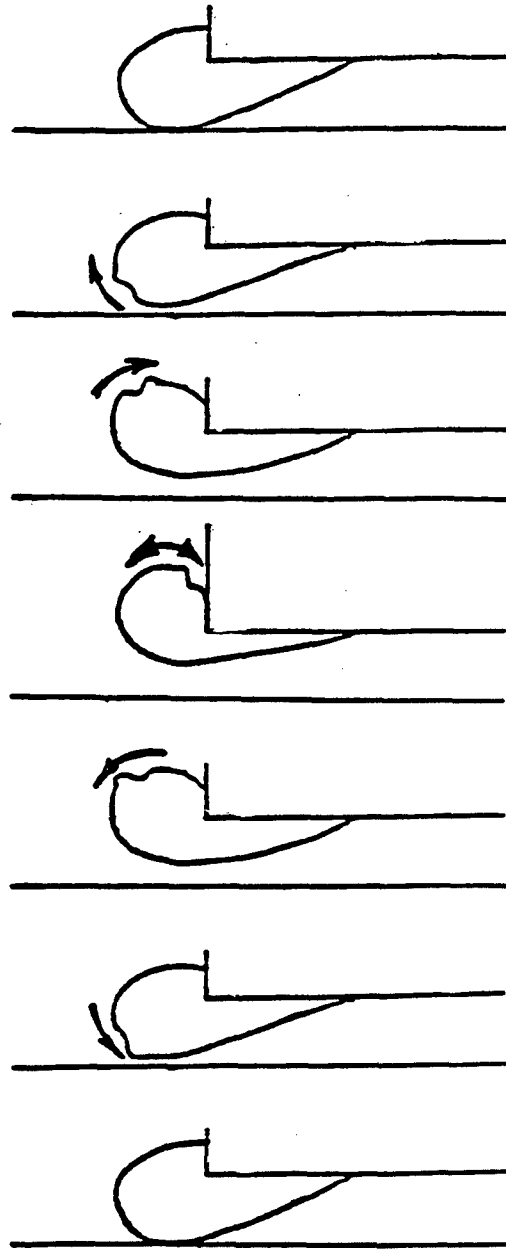


FIGURE 6. TRUNK INFLATED OUT of GROUND EFFECT

TIME



**FIGURE 7. SMALL RIPPLE VISIBLE in OUTER TRUNK PANEL**

### SECTION III ANALYTICAL MODEL

Several models of flutter have been proposed. The first examines air fabric interaction near the ground plane. If a "negative stiffness" induced by the air flow under the trunk exceeds the positive stiffness induced by inflation pressure, flutter will result. A Foster-Miller Associates, Inc., computer program (see References 10 and 11) considers variables including trunk material properties, shape, trunk and cushion flow rates, pressure fields, ground clearances to hard structure, and active/passive control elements. An apparent program error blocked comparisons between the program output and data recorded here. Time did not allow for an exhaustive review of the error.

System sensitivity to operating conditions suggested above was seen during a simple test of the 3D model in Figure 2. Under light load, flutter was located only near the fan ducts. When the model was rolled about its longitudinal axis by pressing down on the tubular member at the rear of the model, flutter spread until the entire trunk length was involved. Similarly, different ground features (tall grass vs smooth concrete) have produced different amounts of bag motion (see Reference 1). The Foster-Miller program can be improved by including trunk and ground elements in the analysis.

Flow instability near the ground plane may feed back into the supply, and create the negative stiffness considered above. The flow would alternately attach to the opposite side walls, the ground and the trunk membrane. If the induced stiffness is greater than inflation induced positive stiffness in the trunk, flutter will again occur. Forcing the air to remain attached to the trunk well beyond the ground plane (see Figure 8) was attempted in one test. The velcro tabs were not able to hold the panel in place under operating conditions. If it can be used successfully, this procedure might change the foot print and cushion pressure. A stiff panel hand held like the flexible panel in Figure 8 did reduce flutter. See

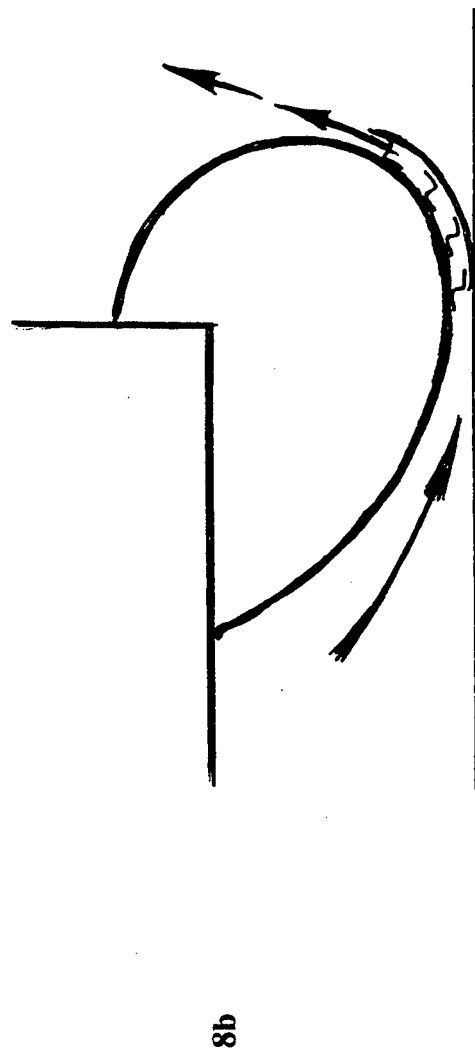
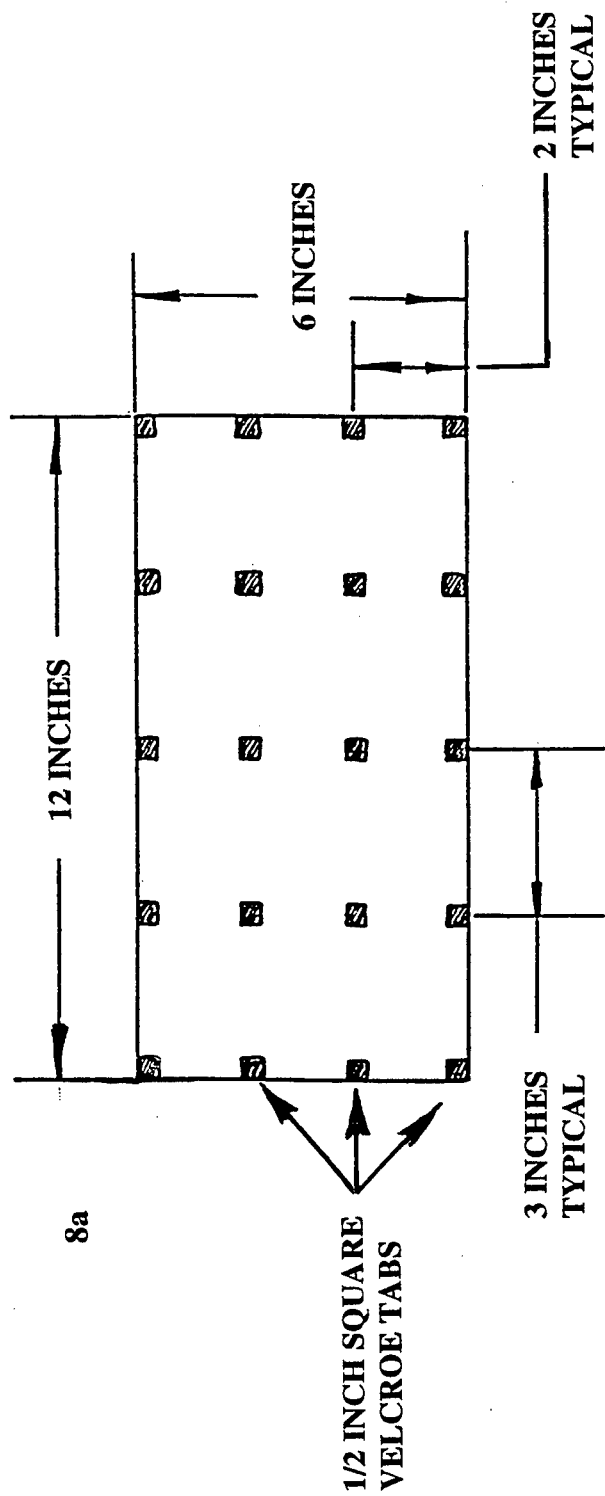


FIGURE 8. VELCROE PANEL (a) and ATTACHMENT to TRUNK (b)

Reference 12.

Finally, flutter may be attributed to vortex shedding downstream of the ground tangent point on the inflated trunk. See Figure 6. Using the von Karman relationship for a cylinder of diameter  $D$  (ft) measured perpendicular to the flow, the frequency of oscillation  $f$  (Hz) may be related to the fluid velocity  $V$  (ft/sec) as:

$$f = 0.207 V/D$$

On a standard day, the velocity may be related to the cushion pressure  $P$  (psfg) by:

$$V = 29 \sqrt{P}$$

The normal range of Reynolds number when the von Karman model is used runs 2000-5000; these tests were completed at levels 100 times that range or higher. In the XC-8A tests where there was good agreement, the trunk was an elastic model. As noted above, the trunk material (NRV-1814) was in an inelastic range of loading here. See References 1 and 8, Appendix B. The error between calculated and observed frequencies increased from 8% (for the simple trunk) to 38% (for the trunk with several control elements attached). The inconsistent error suggests that the von Karman model is not applicable to this program. See Reference 12.

## SECTION IV TEST EQUIPMENT SETUP

### 1.0 Flutter Rig

The rig was designed for separate control of several test variables. A movable floor, twin independent air supplies, and easily moved inner and outer attachment points were available. A general rule suggested that the length of the trunk should be a minimum of two and one-half (2-1/2) to three (3) diameters long (see Figure 6), when compared to the trunk inflated out of ground effect. Test instrumentation and the rig design permitted easy numerical and subjective observations to be made. The cushion volume was large enough to maintain constant pressure normally assumed for an air cushion system. Because of the rig design and the fabric mechanical properties, any change in performance may be credited to the test article: strakes, weights, etc.

The structure was made of three quarter (3/4) inch thick A-D plywood. One side wall was mylar coated with clear lexan plastic to permit observation and photography. The opposite plywood wall was faced with Teflon to reduce the sliding friction with the bag. The movable floor could be adjusted vertically with screw jacks through a range of zero (0) to twenty eight (28) inches of clearance to the hard structure. The sides of the floor panel had rubber strip seals installed to virtually eliminate leakage around the edges. The panel was held against the back wall of the rig by tightening cables between two "T" channel beams with turn buckles.

### 2.0 Air Supply (See Figure 9)

Unlike some other studies, these tests were run on a continuous flow system. Air was supplied by an aftercooled Allis-Chalmers Turbo Blower, capable of 9600 cfm at 31.1 psig.

A 1500 gallon damping tank was used to eliminate supply line pressure perturbations. Flutter has occurred with a constant pressure supply (as here) and a bladed fan supply

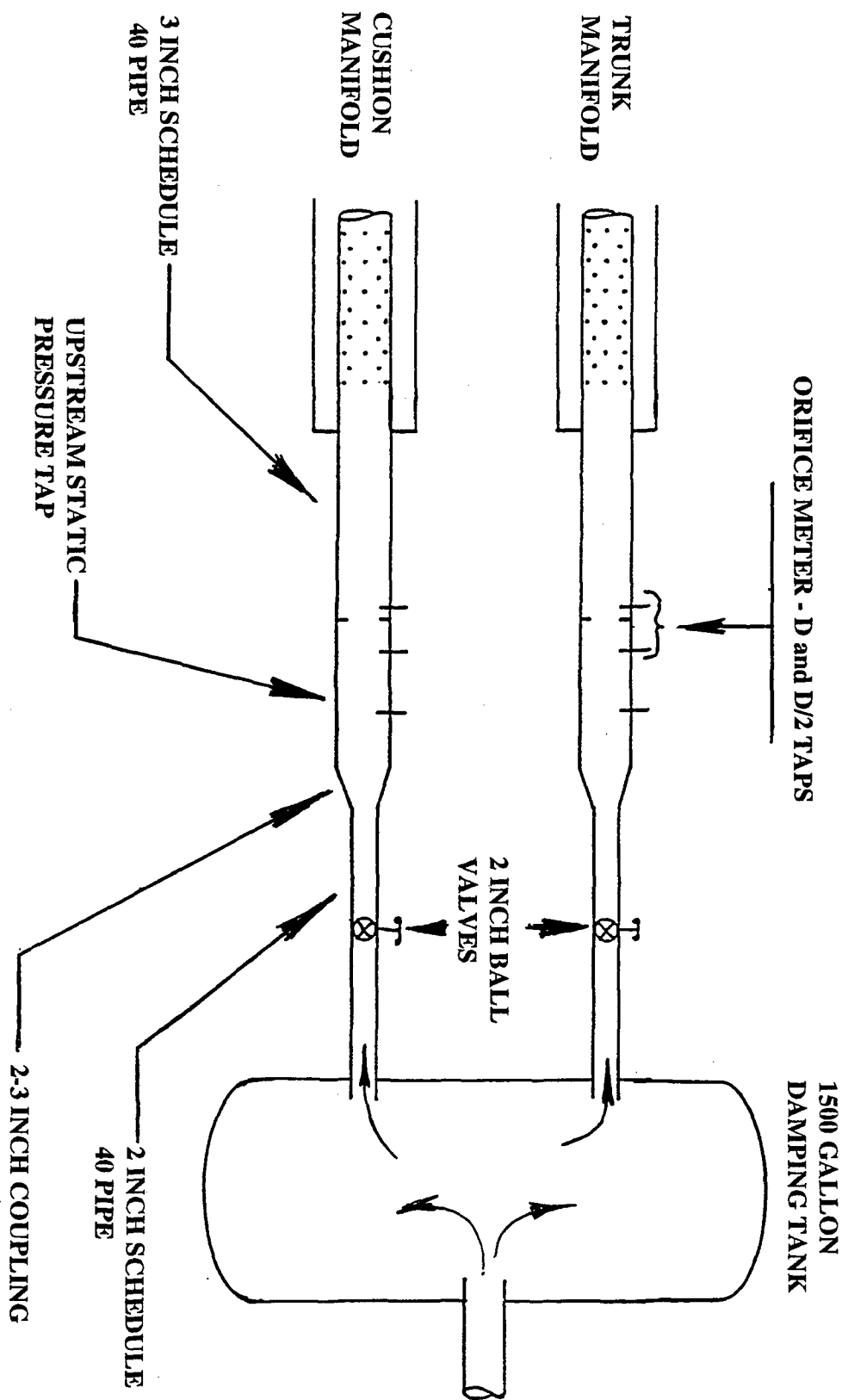


FIGURE 9. AIR SUPPLY SYSTEM

system (see Reference 1).

Separate, identical lines fed the trunk and cushion manifolds. A two (2) inch diameter schedule forty (40) pipe (0.154 inch thick wall), with a ball valve for flow control, led from the damping tank, through a short expansion, into the three (3) inch diameter schedule forty (40) pipe (0.216 inch thick wall). The metering orifice was in the three inch line. Inside the manifold box, a series of 100, 1/4 inch diameter holes were drilled in ten rows that were evenly spaced along the length and around the circumference of the pipe. A parabolic entrance curve directed air smoothly and slowly (12 ft/sec at maximum flow) into the test sections.

## SECTION V TEST INSTRUMENTATION

### 1.0 Air Flow

Air flow through the system was measured in the three (3) inch line with a standard ASME thin plate orifice equipped with D and D/2 pressure taps. A separate static tap was several diameters upstream. The meter was built with  $\beta$  ratio of 0.7008. Pressure measurements were taken from a mercury tube manometer marked in 0.1 inch increments (see References 13 and 14).

### 2.0 System Pressures

Pressures in the trunk and cushion, and along the instrumentation slide in the floor were measured on a ninety-six (96) inch water tube manometer marked in 0.1 inch increments. An incline manometer sensitive to 0.002 inches of water was installed to look for the point of flutter initiation. The fluid in the manometer could not follow the fast fluctuating pressure signal, however, and all that resulted was a general stirring of the water in the end of the manometer. The instrumentation slide could be moved through five (5) inches of travel parallel to the air flow. Twenty-seven (27) ports were spaced at one (1) inch intervals along the slide. The ports ranged from well in the cushion to out in the free air.

### 3.0 Temperature

A mercury thermometer was installed in the lid of the trunk air manifold, but violent motions of the rig broke two of them. A temperature sensor at the blower aftercooler was used throughout these tests. Thermometer readings ranged between 75-95°F when it was in place. The aftercooler sensor was used to keep the air in this range throughout the program.

### 4.0 Visual Data Collection

A sheet of clear film was marked with a two (2) inch X-Y grid and secured to the outside of the lexan side wall. This helped in leveling the movable floor and in tracing the

motion of the nodal points on the trunk.

White thread lines were sewn in the trunk carcass perpendicular to the airflow, one line intersecting at each nodal point. The nodes were used as inputs to the Foster-Miller program. Yarn tufts were attached near the center of the bag near the ground plane to help monitor flow near the surface of the bag.

A General Radio model 1546 strobe light was used to observe the mode shapes and to determine the primary frequency of heave. It was indexed in increments of one (1) cycle per minute. It was used to freeze the motion when checking for the maximum air gap at the center of the bag.

Very high speed movies were used to record the bag motion. An accelerometer was attached to the center of the trunk near node 6 to precisely record the frequency and amplitude of the motion. The violent motion quickly tore it loose and destroyed it. No replacement was installed. This experiment with accelerometers was similar to tests on the XC-8A aircraft.

Finally, a calibrated square was used to measure the maximum air gap under the trunk near the center. The scale was indexed in increments of 1/16 inch.

## **SECTION VI TEST TRUNK**

### **1.0 Trunk Carcass**

The trunk carcass was made of Snyder NRV-1814, a nylon reinforced vinyl fabric that weighs eighteen (18) ounces per square yard. The piece was of uniform construction throughout.

The trunk material was installed with the reinforcing threads, the warp, parallel to the flow. A row of seventeen evenly spaced cushion orifices one (1) inch in diameter was cut at a distance of two (2) inches from the inner attachment point. The smaller trunk orifices were cut between nodes 3 and 12, in the ground contact region. See Figure 10.

Inner and outer attachments were made by sewing a bead into the fabric, sliding a wooden dowel into the bead, and clamping the trunk into the side of the rig with an aluminum strip that was notched to hold the dowel. Cuffs on the ends of the bag were adjusted with a draw string to prevent leakage along the side wall and to maintain a uniform shape of the trunk near the ends.

### **2.0 Trunk Modifications**

A variety of passive elements were added to the trunk. They were held in place by velcro tabs, rubber cement, and duct tape. Tests were run to evaluate individual and combined controls.

#### **2.1 Sawtooth Panels (See Figure 11)**

Panels of a material similar to the trunk carcass, but heavier (31 ounces per square yard), were cut into sawtooth shapes for installation near the inner and outer attachment points. Using an X-Y grid, sharp corners were placed at prime number intervals, i.e. 3 inches between points, 5 inches, 7 inches, etc. By using this vibration isolation technique, any system natural frequencies can be driven to very high levels. Past experience is that

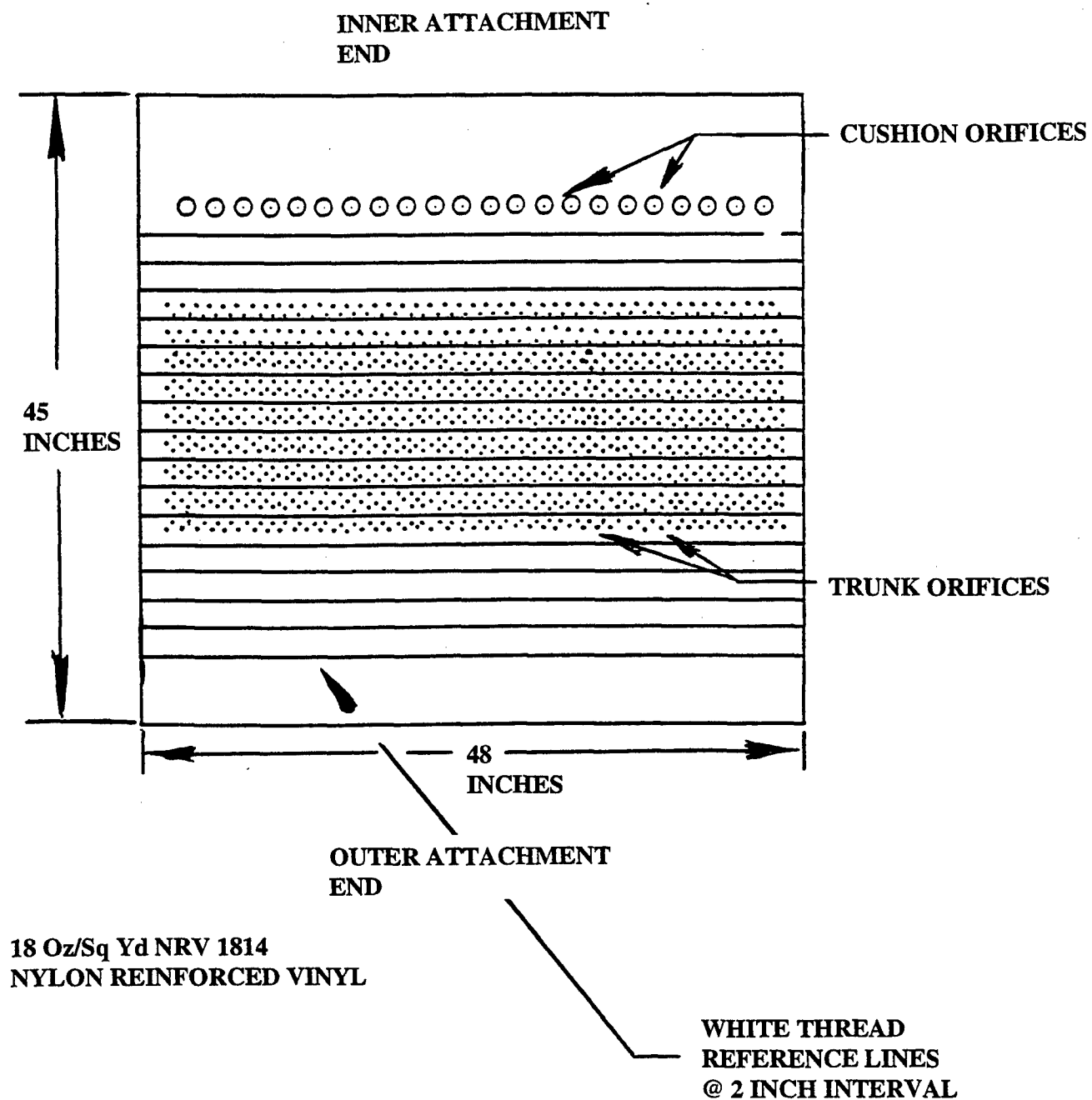
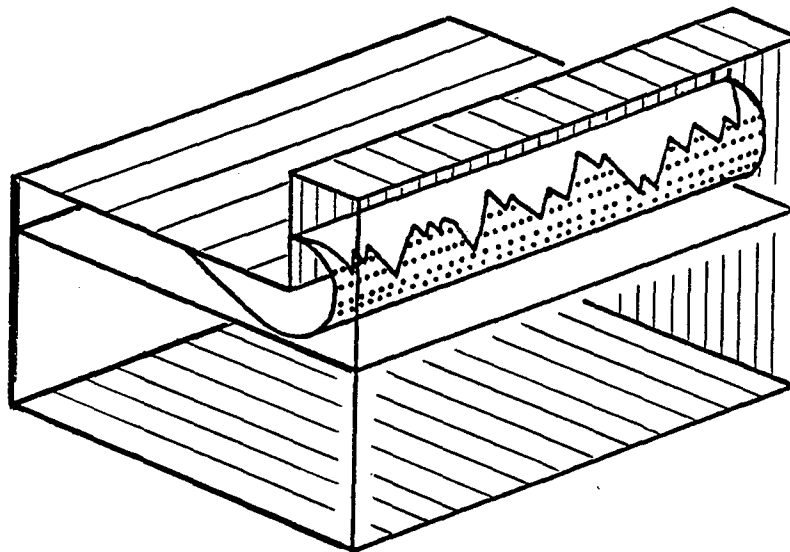
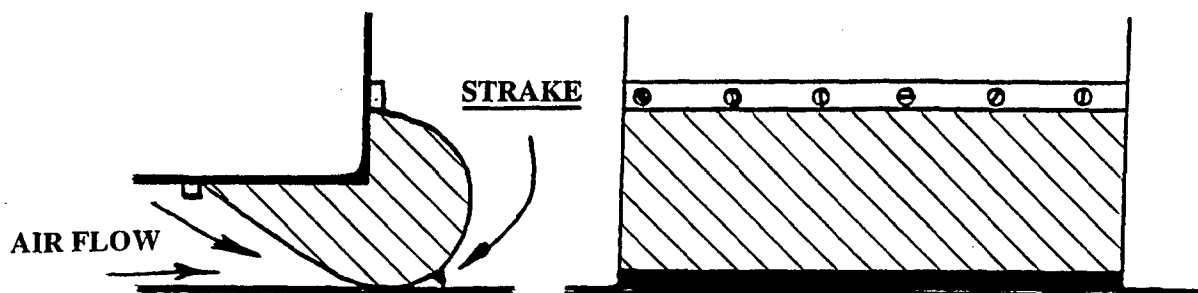


FIGURE 10. 1/4 SCALE TRUNK



**FIGURE 11. SAWTOOTH PANEL MOUNTED  
at OUTER ATTACHMENT POINT**



**FIGURE 12. STRAKE MOUNTED ACROSS  
FULL WIDTH of BAG**

flutter is a "low" frequency phenomenon, 12-30 Hz. See References 1 and 12.

## **2.2 Strake (See Figure 12)**

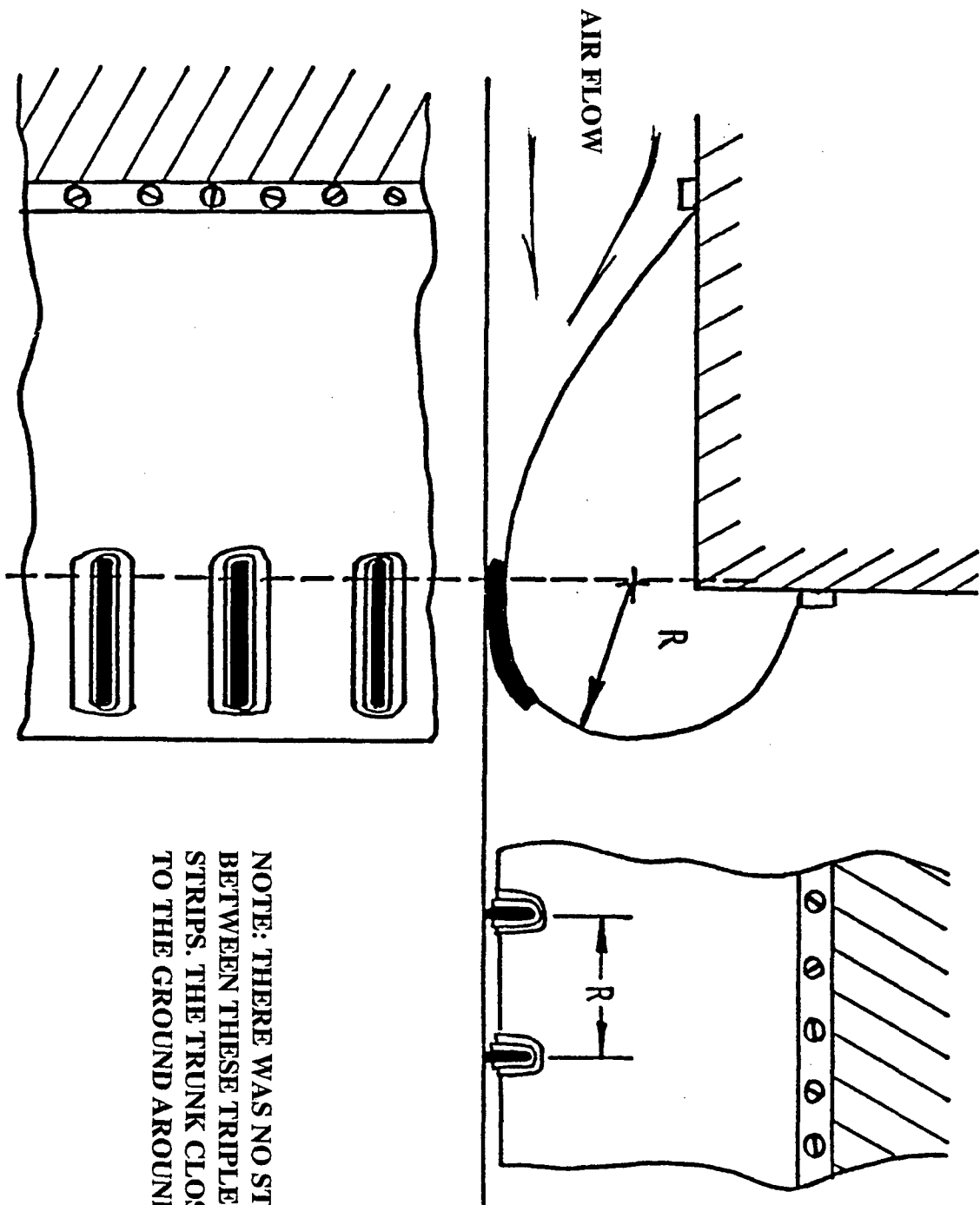
A single strake measuring one-half ( $1/2$ ) by three-sixteenths ( $3/16$ ) inches was installed the full width of the trunk. It was situated  $10-12^\circ$  outside of the ground tangency line (node 6). Yarn tufts were helpful in locating the strip.

## **2.3 Tread Strips (See Figure 13)**

Tests indicated that ground contact ranged from a line contact at node 6, to a strip between nodes 6 and  $7-1/2$ , no matter what the ground clearance was. Using the OGE radius of eight (8) inches seen in Figure 6, laminated strips were attached to the trunk parallel to the flow, four (4) and eight (8) inches apart. The same material that was used for the sawtooth panels (see Section 2.1) was applied in single, double, and triple layers at the  $1/2R$  and  $R$  spacings. The tread strips were eight (8) inches long so that they bridged the ground contact area of the trunk. They were attached between nodes 5 and 9 in strips one-half ( $1/2$ ), three-quarters ( $3/4$ ), and one (1) inch wide. No stiffener was installed to keep the trunk from contacting the ground between the strips.

## **2.4 Weights**

Individual, 0.12 ounce lead weights were taped to the trunk in a variety of patterns: twenty weights were equally spaced along node 12; in combination with a single outer saw tooth panel, as many as ten weights were taped to each point of the sawtooth panel.



NOTE: THERE WAS NO STIFFENER  
BETWEEN THESE TRIPLE TREAD  
STRIPS. THE TRUNK CLOSED DOWN  
TO THE GROUND AROUND THE STRIPS

FIGURE 13. TREAD STRIPS at 'R' SEPARATION

## SECTION VII TEST SCHEDULE

### 1.0 Calibration

The movable floor was dropped far enough below the inflated trunk that the cushion pressure was zero (0) inches of water gauge (out of ground effect, OGE, condition). Flow through the trunk was tested by alternately blocking the trunk and cushion orifices. The trunk was pressurized to the anticipated eight (8), ten (10), twelve (12), and fourteen (14) inches of water. Flow data was recorded, the tape removed, and the floor raised for full scale flutter tests.

Originally, flow control was to have been accomplished by choking the 100 distribution holes across the pipe in the overhead manifold box. Inadequate blower pressure forced a change to control via the ball valve that was installed in each supply line.

With the floor raised close enough to create a cushion pressure (in ground effect, IGE, condition) behind the trunk, testing began. At each combination of trunk pressure and ground clearance, the flutter became much worse when secondary cushion air was added. After a few preliminary test points, the cushion air system was blocked and not used again during the rest of the program.

### 2.0 Test Sequence

Individual runs were made by adjusting the floor level and setting a trunk pressure with no damping on the fabric. Damping was accomplished by test personnel pressing their hands on the carcass until the large amplitude heave stopped, or, in one test sequence, by tying a 2x4 board to the bag. This damping force varied according to the efficiency of the pressure control element(s).

The floor was set at six (6), eight (8), and ten (10) inches of ground clearance. The undamped trunk pressure was set at eight (8), ten (10), twelve (12), and fourteen (14)

inches of water, gage. A line of data included the following: pressure upstream of and across the orifice, pressures in the trunk and cushion volumes, a  $\Delta p$  between the trunk and cushion, frequency of the heave, and maximum air gap near the center of the bag. The air temperature was checked occasionally to assure that it wasn't wandering greatly. General comments were recorded at this time, i.e., bag contacting ground between nodes 6 and 7. Damping was added and another line of data was taken. The air flow was only shut off long enough to add or remove a passive control element. A record of the runs is presented in Appendix C. Data was reduced using standard techniques. A sample flow calculation is presented in Appendix D. See References 13 and 14.

## SECTION VIII TEST RESULTS

The performance of the trunk may be separated into three areas of interest: cushion pressure, maximum air gap, and frequency of oscillation, as related to air flow.

### 1.0 Cushion Pressure

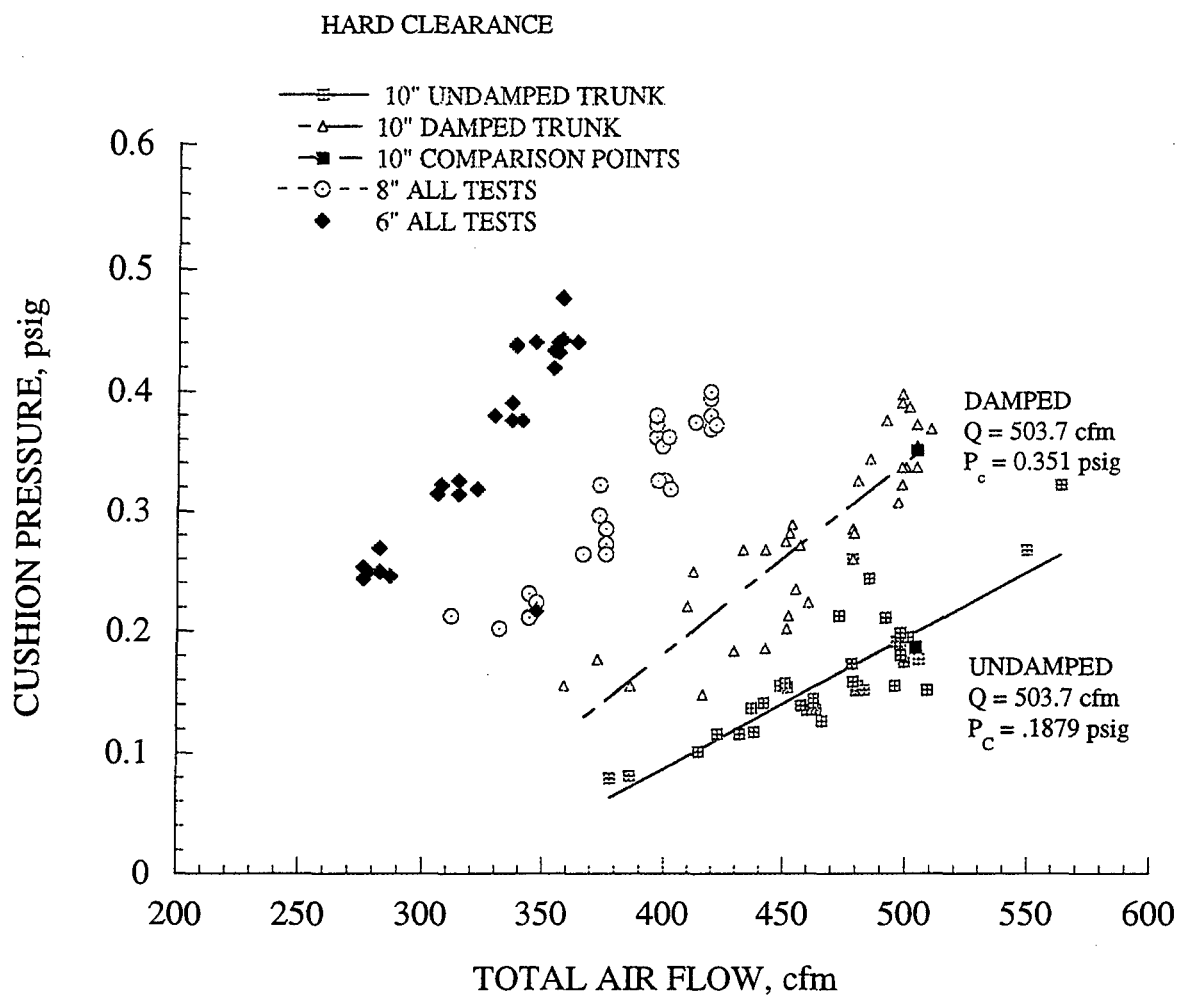
In Figure 14, the scatter of data becomes less as the ground clearance is reduced. Damped and undamped tests at six (6) inches clearance needed 285 cfm to maintain 0.23 - 0.25 psig cushion pressure; conversely, with ten (10) inches clearance at 503.7 cfm, the cushion pressure varied between 0.351 and 0.188 psig, a 9% load capacity vs an 87% change. At the ten inch clearance, the amount of change in load bearing pressure in damped and undamped tests ranged between 40% and 104% difference as the several controls were tried.

### 2.0 Maximum Air Gap

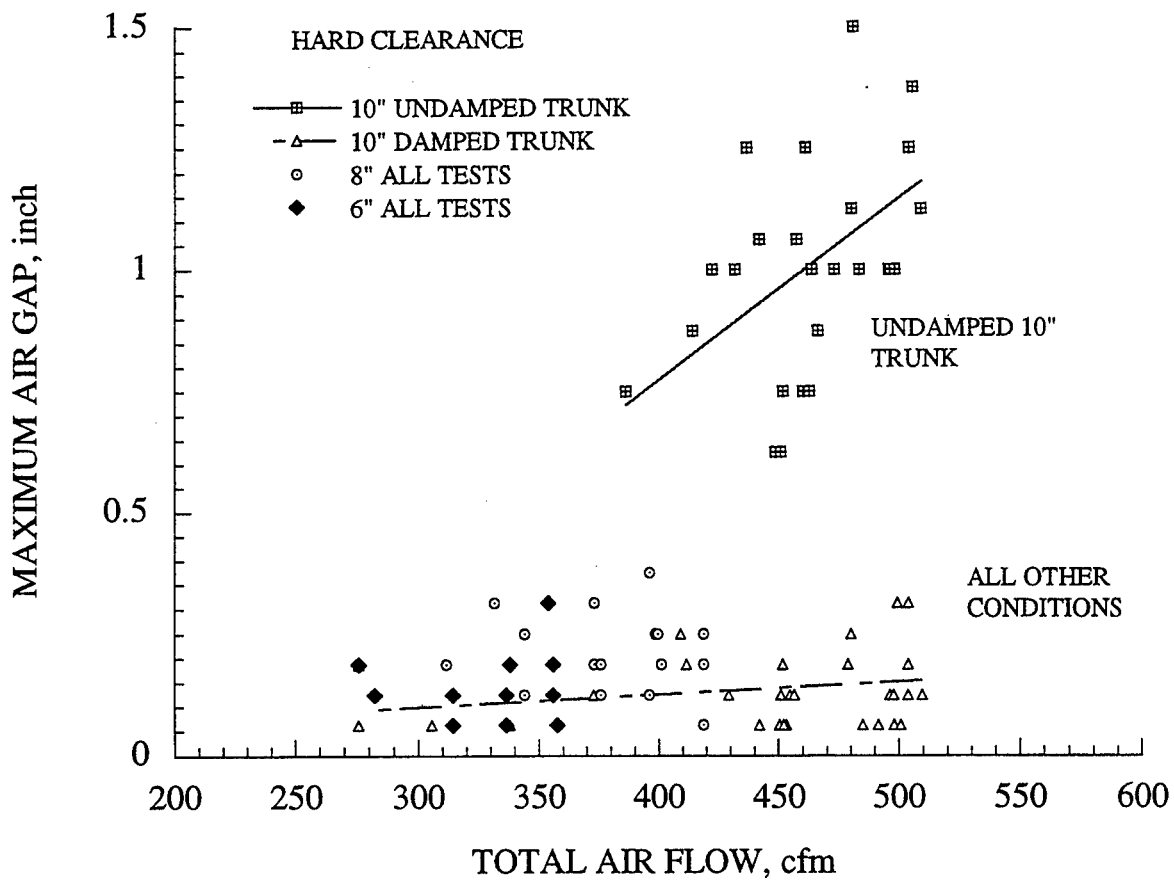
The air flow - air gap relation generally follows a linear relationship, as would be expected. In the 10 inch clearance tests, however, a condition was reached at which the system diverges radically when undamped. Scatter of the data results from the efficiency of the control elements. A 10-to-1 increase in air gap was noted between damped and undamped tests with 10 inch clearance. See Figure 15.

### 3.0 Frequency of Oscillation

The frequency of heave oscillation shows little scatter in Figure 16. The control elements effected the air flow but not the spring constant of the trunk carcass until sawtooth panels (with and without weights) were added. Figure 17 suggests a spring model (see Reference 9). Again, Figure 15 shows a change of the spring constant and damping as air flow reached a breakaway value. The tremendous increase of air gap also saw a drop in the frequency, therefore, internal fabric damping couldn't restrain the trunk.



**FIGURE 14. TOTAL AIR FLOW vs CUSHION PRESSURE**



**FIGURE 15. TOTAL AIR FLOW vs MAXIMUM AIR GAP**

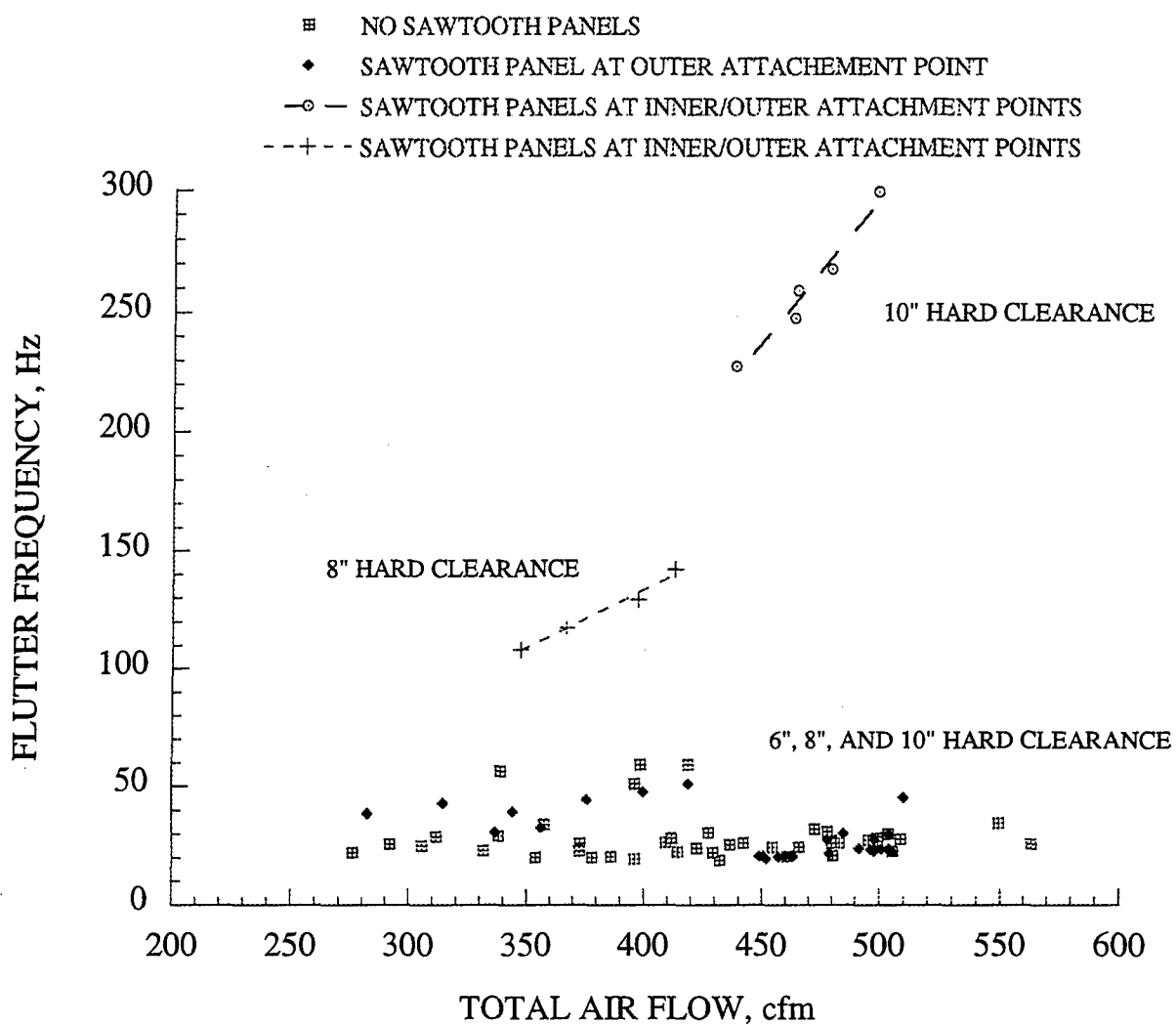
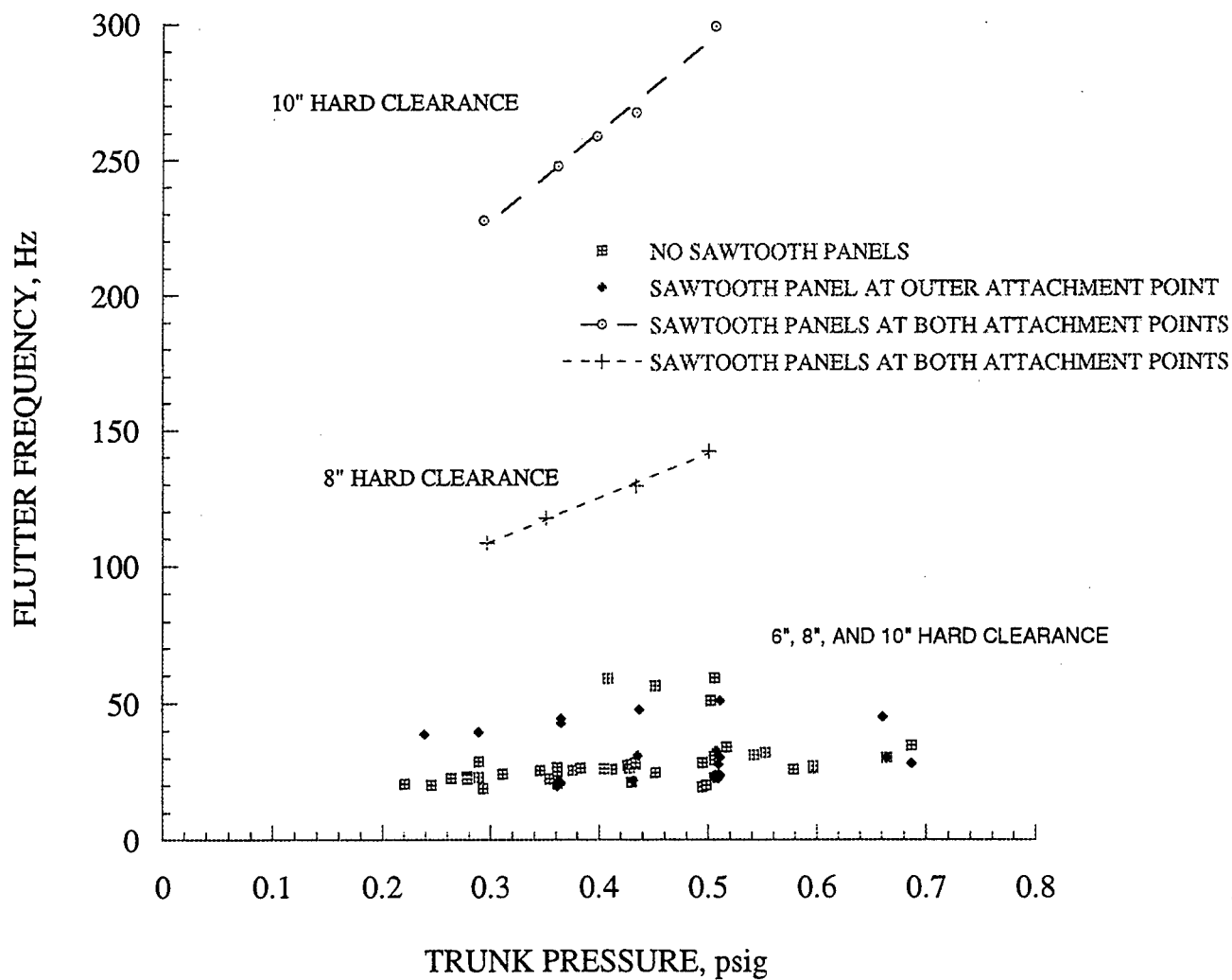


FIGURE 16. TOTAL AIR FLOW vs FLUTTER FREQUENCY



**FIGURE 17. TRUNK PRESSURE vs FLUTTER FREQUENCY**

## **SECTION IX CONCLUSIONS AND OBSERVATIONS**

### **1.0 Conclusions**

Based on these experiments, and other similar studies, the following conclusions may be drawn concerning trunk flutter:

1.1: Flutter is sensitive to ground plane flow/fabric tension interactions. At a given trunk pressure, the addition of extra cushion flow will aggravate flutter.

1.2: Passive elements will change the system operating conditions, with great sensitivity to the clearance between the hard structure and the ground. These elements individually or together will reduce the active control force needed to stop flutter entirely.

1.3: Control elements that are most effective work by increasing the stiffness and/or internal damping of the trunk carcass (sawtooth panels), act as a flow tripper to fix the separation point (strakes) and preserve continuous flow under the trunk (tread strips).

### **2.0 Observations**

2.1: Flutter is not related to any air supply perturbations. The amplitude and frequency of flutter on this 2-D rig and the bladed fan-supplied 3-D rig were of similar magnitude.

2.2: Active control force needed varies with the efficiency of the passive elements. The damping force generally ranged between 1-1/2 - 12-1/2 pounds. In one test with double sawtooth panels at both attachments, the trunk did not begin to flutter until it was slapped. It could be stopped by the pressure of one finger at the center of the bag.

2.3: The intent of tread strips is to assure continuous flow under the bag. The flexible

trunk material sealed around the strips, closing off the channel completely, briefly, during several runs.

2.4: A narrow strip of the trunk is always near the ground plane, regardless of the ground clearance or trunk pressure. The effectiveness of a strake or tread strip may depend greatly on the flexibility of this small section of the trunk. Trunk life may also depend on the durability of this area.

2.5: Internal damping may effect the response of the trunk. When the trunk was inadvertently mounted so that the reinforcing threads of the NRV-1814 were skewed from the air flow slightly, the nature of the heave changed considerably. No data was taken as this test was set up to have the threads parallel to the flow.

## **SECTION X RECOMMENDATIONS**

### **1.0 Trunk Carcass**

Internal damping may be changed dramatically by mounting the fabric so that the reinforcing threads are on a bias.

The flexibility of the carcass should be changed near the ground plane to assure the position of strakes and tread strips at all times. The addition of mass does change the system, but only at a considerable weight penalty. The goal is a light weight, flutter free system.

### **2.0 External Additions**

Strakes, tread strips, and weights are external control elements. Further tests should be run to see if a narrow strip of trunk carcass does stay near the ground plane regardless of ground clearance. The durability of these elements and ease of replacement will assure an effective trunk system. An internally formed strake (see Figure 18) may be an alternative to the external add-ons tested here. Spacing between tread strips, and their height and width will also effect the weight of the final trunk.

A balance between active and passive control elements will result in a compact, light weight, durable trunk air cushion system.

INTERNALLY MOUNTED PANEL  
PARALLEL TO THE FLOW TO  
FORM A STRAKE NEAR THE  
GROUND PLANE

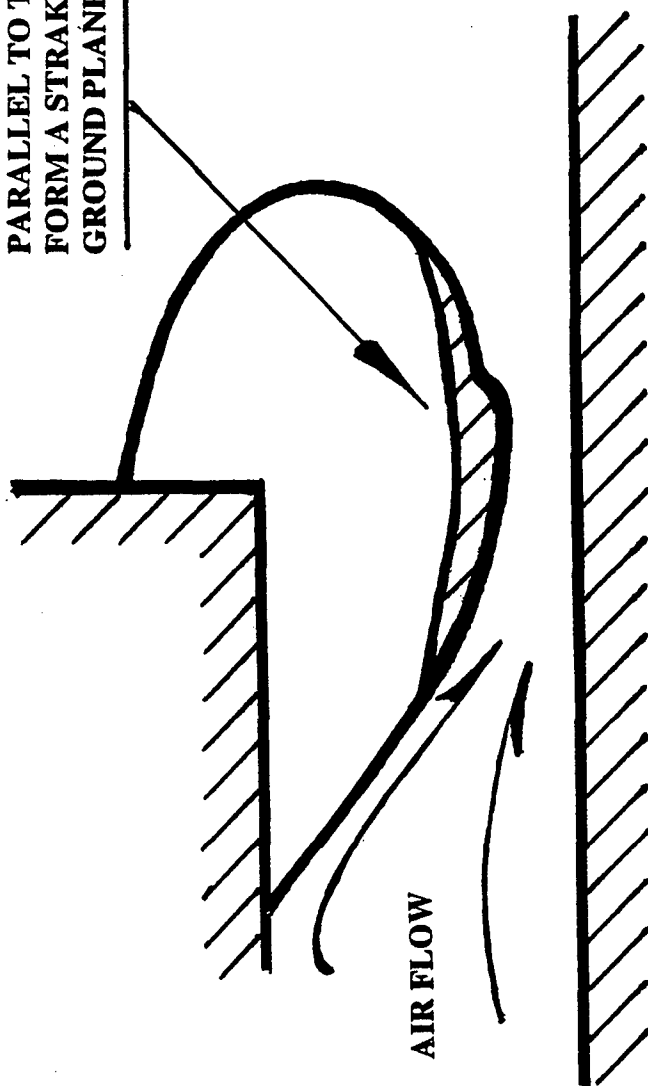


FIGURE 18. INTERNAL STRAKE

## SECTION XI REFERENCES

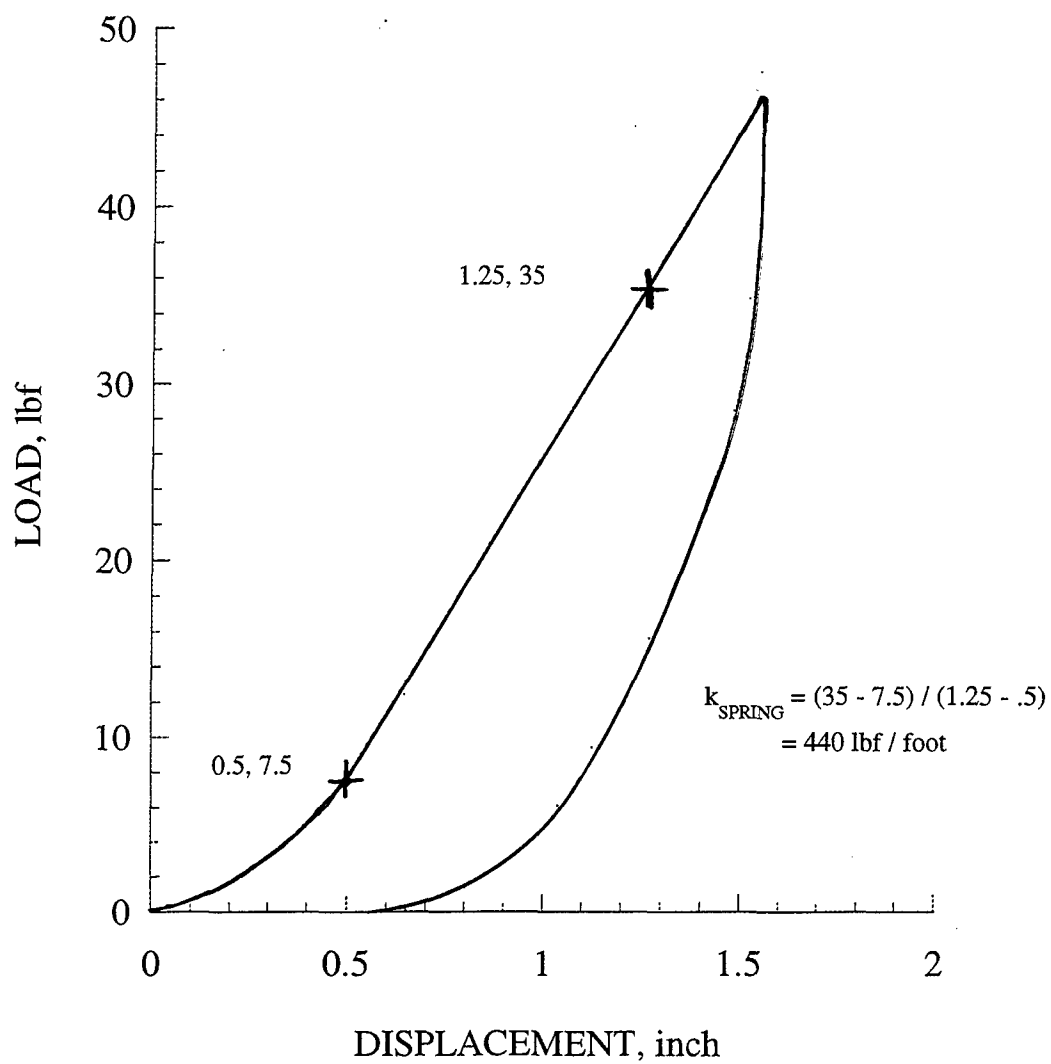
1. Tests of the Air Cushion Landing System of the XC-8A, Wallace C. Buzzard, David J. Perez, Gerald Wyen, and Major John Randell (CAF), AFFDL-TR-78-61
2. An Experimental Investigation of Trunk Flutter of an Air Cushion Landing System, Carmine J. Forzono, AFFDL-TR-75-107
3. Proposed Solutions to Technical Problems Encountered in the XC-8A Air Cushion Landing System Development Program, Major Thomas R. Clapp (USAF), Air Command and Staff College Student Research Report, 0420-80
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## APPENDIX A

### MECHANICAL PROPERTIES OF NRV-1814 as per FEDERAL TEST METHOD 191

Snyder Manufacturing Company, Ltd  
Dover, OH

Initial breaking strength, Lb/1 inch wide sample	310	305
Tearing strength	105	100
Abrasion resistance, percent strength loss after 250 cycles	<10	<10
Weatherometer, percent strength loss after 150 hours	0	0
Adhesion (peel resistance), Lb/2 inch wide sample	30	
Stiffness, centimeters of free length	15.0	
Water (hydrostatic) resistance	425	
Flame retardance, maximum time after flame, seconds	5	
Weight, ounces per square yard	17.1 - 19.8	



**APPENDIX B: LOAD-STROKE CURVE from MATERIALS LABORATORY**

# APPENDIX C TEST DATA

RUN	Q TOTAL AIR FLOW cfm	P <sub>t</sub> TRUNK PRESSURE psig	P <sub>c</sub> CUSHION PRESSURE psig	G MAX AIR GAP inch	F FLUTTER FREQUENCY Hz	C HARD CLEARANCE inch	DAMPED	COMMENT
1	549.3	.6865	.2674	1.125	34.750	10	N	
2	338.8	.4516	.3216	-	56.383	8	N	
3	292.0	.4119	.3469	-	25.933	8	N	
4	508.7	.4300	.1518	1.125	27.700	10	N	
5	563.1	.5781	.3216	.3438	25.833	10	N	
6	495.4	.4336	.1554	1.000	27.667	10	N	
7	499.3	.5962	.3360	.3125	27.100	10	Y	
8	479.8	.4263	.1518	1.125	27.333	10	N	
9	479.8	.5962	.3252	.250	26.267	10	Y	
10	472.6	.5528	.2132	1.000	32.000	10	N	
11	427.5	.5058	.2890	.250	30.583	10	N	
12	436.6	.3758	.1373	1.250	25.550	10	N	
13	411.6	.4336	.2493	.1875	28.283	10	Y	
14	422.4	.3107	.1156	1.000	24.183	10	N	
15	409.1	.3613	.2204	.250	26.433	10	Y	
16	414.2	.2638	.1012	.875	22.533	10	N	
17	372.7	.2890	.1770	.125	22.950	10	Y	
18	377.9	.2457	.0795	1.000	20.217	10	N	
19	396.0	.5022	.3721	.125	51.000	8	Y	
20	398.5	.4085	.3541	.250	59.067	8	N	
21	373.0	.4800	.3216	.1875	-	8	Y	NO HARMONIC MOTION (NHM)
22	373.0	.4047	.2963	.3125	27.117	8	N	
23	603.9	.3613	.2746	.1875	-	8	Y	NHM
24	603.9	.3450	.2529	.3125	25.400	8	N	
25	311.5	.2890	.2132	.1875	28.750	8	Y	
26	331.5	.2782	.2023	.3125	23.100	8	N	
27	338.0	.5058	.4390	.0625	-	6	Y	NHM
28	338.0	.5058	.4372	.1875	29.283	6	N	
29	305.5	.3613	.3143	.0625	25.100	6	Y	
30	275.8	.2890	.2529	.0625	-	6	Y	NHM

APPENDIX C Continued

RUN	Q TOTAL AIR FLOW cfm	P <sub>t</sub> TRUNK PRESSURE psig	P <sub>c</sub> CUSHION PRESSURE psig	G MAX AIR GAP inch	F FLUTTER FREQUENCY Hz	C HARD CLEARANCE inch	DAMPED	COMMENT
31	275.8	.2782	.2439	.1875	22.367	6	N	
32	385.8	.2890	.1554	-	-	10	Y	
33	385.8	.2204	.0810	.750	20.617	10	N	
34	432.7	.5058	.2674	-	-	10	Y	NFM
35	441.9	.3830	.1409	1.0625	26.233	10	N	
36	396.0	.5058	.3794	-	-	8	Y	NFM
37	396.0	.4950	.3613	.375	19.633	8	N	
38	353.9	.5058	.4336	-	-	6	Y	
39	353.9	.4986	.4191	.3125	20.267	6	N	
40	505.2	.5058	.1770	1.375	22.917	10	N	
41	503.7	.6648	.3360	.3125	30.100	10	Y	NFM
42	480.4	.4300	.1554	1.500	21.133	10	N	
43	478.1	.5420	.2854	-	31.133	10	Y	
44	460.7	.3613	.1373	1.250	20.500	10	N	
45	454.7	.4516	.2349	.125	24.700	10	Y	
46	431.9	.2927	.1156	1.000	18.833	10	N	
47	429.2	.3541	.1843	.125	22.383	10	Y	
48	503.7	.5058	.1879	1.250	23.267	10	N	SAWTOOTH @ OUTER RATCH (OSAW)
49	503.7	.6503	.3541	.1875	-	10	Y	O SAW
50	505.2	.5058	.1770	1.375	22.917	10	N	O SAW
51	503.7	.6648	.3360	.3125	30.100	10	Y	O SAW
52	418.8	.5112	.3794	.250	51.117	8	N	O SAW
53	418.8	.5365	.3992	.1875	-	8	Y	O SAW
54	399.4	.4372	.3252	.250	47.767	8	N	O SAW
55	400.9	.4751	.3616	.1875	-	8	Y	O SAW
56	375.6	.3649	.2728	.1875	44.467	8	N	O SAW
57	375.6	.3848	.2854	.125	-	8	Y	O SAW
58	344.1	.2890	.2114	.250	39.567	8	N	O SAW
59	344.1	.2999	.2312	.125	-	8	Y	O SAW
60	356.0	.5076	.4400	.1875	32.817	6	N	O SAW

APPENDIX C Continued

RUN	Q TOTAL AIR FLOW cfm	P <sub>t</sub> TRUNK PRESSURE psig	P <sub>c</sub> CUSHION PRESSURE psig	G MAX AIR GAP inch	F FLUTTER FREQUENCY Hz	C HARD CLEARANCE inch	DAMPED	COMMENT
61	356.0	.5528	.4323	.125	-	6	Y	O SAW
62	336.6	.4354	.3758	.125	31.000	6	N	O SAW
63	336.6	.4480	.3902	.0625	-	6	Y	O SAW
64	314.2	.3649	.3143	.125	42.900	6	N	O SAW
65	314.2	.3758	.3252	.0625	-	6	Y	O SAW
66	282.2	.2390	.2493	.125	38.750	6	N	O SAW
67	282.2	.3071	.2692	.125	-	6	Y	O SAW
68	503.8	.5094	.1861	1.250	24.067	10	N	DBL SAWTOOTH @ OUTER ATTCH (DSAW)
69	503.8	.6756	.3721	.125	-	10	Y	D SAW
70	463.3	.3613	.1355	1.000	20.883	10	N	D SAW
71	456.5	.4805	.2710	.125	-	10	Y	D SAW
72	497.9	.5058	.1807	1.000	23.800	10	N	DS AND SNGL TREAD STRIP @ 8" (STR)
73	497.9	.6937	.3974	.0625	-	10	Y	D SAW, STR
74	459.8	.3613	.1355	.750	20.717	10	N	D SAW, STR
75	453.1	.4932	.2890	.0625	-	10	Y	D SAW, STR
76	497.8	.5112	.1915	.750	23.933	10	N	D SAW, DBL TREAD STRIP @ 8" (DTR)
77	497.8	.6865	.3902	.125	28.167	10	Y	D SAW, DTR
78	457.1	.3613	.1391	1.0625	20.60	10	N	D SAW, DTR
79	450.3	.4769	.2746	.0625	-	10	Y	D SAW, DTR
80	500.6	.5058	.1951	.750	23.883	10	N	D SAW, TRPL TREAD STRIP @ 8" (ITR)
81	500.6	.6756	.3866	.0625	-	10	Y	D SAW, TTR
82	462.4	.3649	.1445	.750	20.717	10	N	D SAW, TTR
83	452.1	.4841	.2818	.0625	-	10	Y	D SAW, TTR
84	491.5	.5094	.2114	.750	24.000	10	N	D SAW, TRPL TREAD @ 4" (THR)
85	491.5	.6630	.3758	.0625	-	10	Y	D SAW, THR
86	448.7	.3613	.1554	.625	20.733	10	N	D SAW, THR
87	442.0	.4661	.2674	.0625	-	10	Y	D SAW, THR
88	450.6	.3613	.1572	.625	20.900	10	N	D SAW, THR
89	484.9	.5112	.2439	.500	30.433	10	N	THR
90	484.9	.6251	.3432	.0625	-	10	Y	THR

APPENDIX C Continued

RUN	Q TOTAL AIR FLOW cfm	P <sub>t</sub> TRUNK PRESSURE psig	P <sub>c</sub> CUSHION PRESSURE psig	G MAX AIR GAP inch	F FLUTTER FREQUENCY Hz	C HARD CLEARANCE inch	DAMPED	COMMENT
91	497.8	.5058	.1897	.750	22.950	10	N	D SAW
92	497.8	.6251	.3216	.125	-	10	Y	D SAW
93	451.6	.3613	.1536	.750	19.800	10	N	D SAW
94	450.8	.4083	.2023	.125	-	10	Y	D SAW
95	451.6	.3794	.2132	.1875	-	10	Y	D SAW
96	357.5	.5167	.4426	.0625	34.050	6	N	
97	357.5	.5474	.4769	-	-	6	Y	
98	418.8	.5058	.3685	.250	59.183	8	N	
99	418.8	.5383	.3938	.0625	-	8	Y	
100	499.3	.4950	.1752	.750	28.367	10	N	
101	483.2	.4281	.1518	1.000	26.383	10	N	
102	465.8	.3613	.1265	.875	24.450	10	N	
103	496.3	.5058	.1915	1.000	23.517	10	N	O SAW
104	496.3	.5058	.3071	.125	-	10	Y	O SAW
105	478.8	.4318	.1590	.750	21.750	10	N	O SAW
106	478.8	.5456	.2818	.1875	-	10	Y	O SAW
107	497.8	.5094	.1987	.750	22.717	10	N	D SAW
108	497.8	.6359	.3360	.125	-	10	Y	D SAW
109	478.1	.5094	.2601	.1875	27.867	10	N	D SAW, 15 WEIGHTS ADDED (WT)
110	509.6	.6612	.3360	.1875	45.200	10	N	D SAW, WT
111	509.6	.6973	.3685	.125	-	10	Y	D SAW, WT
112	478.1	.5094	.2601	-	-	10	Y	D SAW, STRAKE ADDED (SK)
113	460.0	.4408	.2240	-	-	10	Y	D SAW, SK
114	442.5	.3613	.1861	-	-	10	Y	D SAW, SK
115	416.0	.2890	.1481	-	-	10	Y	D SAW, SK
116	420.9	.5058	.3721	-	-	8	N	D SAW, SK
117	401.7	.4336	.3179	-	-	8	N	D SAW, SK
118	375.6	.3577	.2638	-	-	8	N	D SAW, SK
119	347.1	.2909	.2168	-	-	6	N	D SAW, SK
120	363.6	.5167	.4408	-	-	6	N	D SAW, SK

APPENDIX C Continued

RUN	Q TOTAL AIR FLOW cfm	P <sub>t</sub> TRUNK PRESSURE psig	P <sub>c</sub> CUSHION PRESSURE psig	G MAX AIR GAP inch	F FLUTTER FREQUENCY Hz	C HARD CLEARANCE inch	DAMPED	COMMENT
121	340.8	.4408	.3758	-	-	6	N	D SAW, SK
122	321.9	.3685	.3179	-	-	6	N	D SAW, SK
123	286.5	.2854	.2457	-	-	6	N	D SAW, SK
124	346.3	.5058	.4408	-	-	6	N	D SAW, SK
125	329.1	.4336	.3794	-	-	6	N	
126	307.3	.3667	.3216	-	-	6	N	
127	277.4	.2818	.2493	-	-	6	N	
128	412.4	.5004	.3740	-	142.080	8	N	SAWTOOTH @ IN/OUTER ATCH (IOS)
129	396.8	.4336	.3252	-	129.500	8	N	IOS
130	366.5	.3505	.2638	-	117.600	8	N	IOS
131	347.1	.2963	.2240	-	108.300	8	N	IOS
132	497.6	.5058	.1987	-	299.200	10	N	IOS
133	478.3	.4336	.1734	-	267.500	10	N	IOS
134	462.4	.3613	.1409	-	247.500	10	N	IOS
135	437.9	.2927	.1174	-	227.500	10	N	IOS
136	463.8	.3974	.1590	-	258.700	10	Y	IOS

## APPENDIX D: SAMPLE FLOW CALCULATION

$$Q = 5 * Y * C * A \sqrt{2 * g_c * \Delta p / \rho}$$

Where

Q	Rate of Flow, ft <sup>3</sup> /min
Y	Net Expansion Factor
C	Flow Coefficient
A	Orifice Area, in <sup>2</sup>
g <sub>c</sub>	Gravitational Constant ft-lbm / lbf sec <sup>2</sup>
Δp	Pressure Change Across the Orifice, psi
ρ	Fluid Density in the Pipe, Nom/Pt <sup>3</sup>

For Test Case 1 from the data in **Appendix C**:

$$Q = 5 * (0.835) * (0.7) * (3.6305) \sqrt{2 * 32.2 * 5.4523 / 0.1310} = 549.3 \text{ cfm}$$



**DEPARTMENT OF THE AIR FORCE**  
**AIR FORCE RESEARCH LABORATORY**  
**WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433**


14 March 2000

MEMORANDUM FOR DET 1 AFRL/WST (STINFO)

FROM: AFRL/VAOP

SUBJECT: Reclassification of AFWAL-TM-84-210-FIEM, An Experimental Investigation of Air Cushion Flutter Using a Two-Dimensional Trunk Model, DTIC Number **ADB 240 794**, by Peter C. Vorum

1. The distribution statement on the subject paper should be changed to, "A: Approved for Public Release, Distribution Unlimited." There is no sensitive information contained in the report.
2. At the time Mr. Vorum wrote the paper, I was his Technical Manager. He is now assigned to AFRL/MLBT. You may contact him directly at 59024. If you have any questions, please contact me at the address above, or call 54294.

  
DAVID J. PEREZ, Chief  
Programming Integration Branch  
Integration and Operations Division